Hydrology and Earth System Sciences, 2(1), 77–91 (1998) © EGS

Hydrology & Earth System Sciences

# Major faults and the development of dryland salinity in the western wheatbelt of Western Australia

C.J. Clarke,[1,4] R.J. George,[2] R.W. Bell[1] and R.J. Hobbs[3]

[1] Environmental Science Murdoch University, Murdoch, 6150, Western Australia.
[2] Agriculture Western Australia, PO Box 1231, Bunbury, 6231, Western Australia.
[3] Commonwealth Scientific and Industrial Research Organisation, Locked Bag No. 4 PO Midland, 6056, Western Australia.
[4] Corresponding Author, fax 61 8 93 60 66 90, email C.Clarke@murdoch.edu.au

## Abstract

Dryland salinity poses a major threat to agricultural production in the wheatbelt of Western Australia and much time and effort is expended on understanding the mechanisms which cause it and on developing techniques to halt or reverse its development. Whilst the location of much dryland salinity can be explained by its topographic position, a significant proportion of it cannot. This study investigated the hypothesis that major faults in the Yilgarn Craton represented in aeromagnetic data by intense curvilinear lows explained the location of areas of dryland salinity not explained by topography. Moreover, the causal mechanisms that might underpin a spatial relationship between major faults and dryland salinity were sought.

In one fourth order catchment, nearly 85% of the salinity that was not explained topographically was within 2km of the centre line of a major fault, the remaining 15% being in the other 12km of the catchment. Three groups of similar third order catchments in the western wheatbelt of Western Australia were also investigated; in each case the catchment that was underlain by a major fault had dryland salinity an order of magnitude more than the unfaulted catchment(s). This evidence demonstrates a strong spatial association between major faults and the development of dryland salinity. Other evidence suggests that the underlying mechanism is hydraulic conductivity 5.2 to 2.9 times higher inside the fault zone compared to outside it and shows that geomorphology, salt store, regolith thickness, and degree of clearing are not the underlying mechanisms. In one of the groups of catchments, it has been calculated that an amount of recharge, significant in relation to recharge from rainfall, was entering from an adjacent catchment along a major fault.

The paper concludes that geological features such as major faults affect the development of dryland salinity in the wheatbelt of Western Australia because of permeability differences in the regolith and therefore computer models of salinity risk need to take these differences into account. Techniques need to be developed to map, quickly and relatively cheaply, the geology-related permeability differences over wide areas of the landscape.

## Introduction

Extensive development of secondary dryland salinity in the wheatbelt of Western Australia is a major cause of land degradation (Ferdowsian *et al.*, 1996) and consequent economic loss of agricultural production. Clearing of perennial native vegetation for agriculture has been responsible for the development of dryland salinity. Reduction of interception and evapotranspiration by the loss of the deep rooted, perennial native vegetation has led to an increase in runoff and recharge.

The wheatbelt is underlain predominantly by granites and granitic gneisses of the Archaean age Yilgarn Craton (GSWA, 1990), which is bounded to the west by the Darling Fault and is intersected by a number of major faults which splay off from that fault (Myers, 1989). The Archaean rocks are intruded by numerous mafic dykes (mostly of Proterozoic age) and in many of the valleys they are overlain by sediments of Tertiary age (GSWA, 1990). All of these rocks were subjected to deep weathering during the hotter and wetter Tertiary period and subsequently to intense leaching due to a general drying of the climate (McArthur, 1993). This has produced a characteristic deeply weathered profile in the regolith known as the lateritic profile. This consists, when intact, of partially weathered material , the saprolite, overlying the fresh rock, overlain by the completely weathered pallid zone, which is in turn overlain by the transitional mottled zone, then the iron oxide-rich duricrust and finally the sandy soil layer (McArthur, 1991). This profile has been variably dissected by rejuvenation of the drainage due to uplift on the Darling Fault (Mulcahy *et al.*, 1972).

Wood (1924) recognised all the features of the lateritic profile and postulated that the destruction of native vegetation resulted in the rise of saline groundwaters and the relocation of salts, derived from oceanic aerosols and stored in the groundwater, to the surface. Sixty years later, Peck and Williamson (1987) demonstrated clearly that, in catchments experimentally cleared for agriculture, piezometric surfaces moved upwards (at rates up to 2.6m year$^{-1}$) in response to increased recharge. Evidence for the origin of the salt in the groundwater and the regolith was provided by Hingston and Gailitis (1976). They showed that the accretion rate of salt (primarily sodium and chloride ions) from oceanic aerosols was between 100–250kg ha$^{-1}$ year$^{-1}$ in high rainfall coastal areas, falling to 10–20kg ha$^{-1}$ year$^{-1}$, 300km inland. Johnson (1987) concluded that at these rates of salt accretion, 7,000 to 13,000 years was sufficient to account for the measured salt storage in zones of higher rainfall (>700mm), whilst in the more arid areas (<250mm) McArthur *et al.* (1989) concluded that continuous accretion from the late Pleistocene was necessary. These later papers support the conclusion that Wood's seventy year old hypothesis is still valid today, except that the salt is now known to be stored as much in the regolith as it is in the groundwater (McArthur *et al.*, 1977); George (1992a) stated that the principal aquifer causing dryland salinity in the wheatbelt is the unconfined to semi-confined, coarse grained saprolite aquifer underlain by basement and overlain by the deeply weathered pallid zone of the laterite profile, whereas Wood (1924) thought it was the entire pallid zone.

Other investigations of processes leading to the development of salinised land have focussed on study of this deep aquifer in order to predict where salinisation was liable to develop; whilst it was often found that salinised land developed in lower valley locations and at breaks in slope, topography alone was not sufficient to predict the location of all salinised areas (Barrett-Lennard and Nulsen, 1989). The search for additional features in the landscape that could explain why salinised land occurs in locations not predicted by topography has turned to geology.

In 1987, Engel *et al.* showed that, in a first order catchment (Strahler, 1964), the clay produced by the weathering of dolerite is less permeable than the clay and quartz which are the weathering products of granite and granitic gneiss. They suggested that the weathered dolerite dykes acted as a barrier to groundwater flow, causing groundwater to rise and salinity to develop on the upstream side.

Lewis (1991) and Ferdowsian and Greenham (1992) took this direction of research to the catchment scale. Ferdowsian and Greenham (1992) proposed that saline seeps were associated with fractured rock aquifers with increased hydraulic conductivity ($K_{sat}$) on one side of the fractured zone, whilst it was reduced on the other. Lewis (1991) identified several types of geological features which could create lineaments on aerial photographs, satellite images and maps: basic dykes, quartz dykes and quartzite outcrops, and fracture, shear or fault zones. She suggested that each of these could act as a carrier or barrier (or both) to groundwater flow, and in particular, that carriers could transport water across topographic divides, but how much, how far and how fast were not known.

George (1992b) attempted to answer some of these questions and suggested that, in the East Belka Catchment, groundwater could leave the catchment through the divide, along strike from a major fault, but concluded that there was no surface evidence of a fault within the catchment. He showed that the total flux from the catchment, including that across the topographic divide, was <0.1mm year$^{-1}$, and when sensitivity to transmissivity was taken into account, would not exceed 0.3mm year$^{-1}$. He concluded that, because of this low rate of groundwater flow in the East Belka Catchment, the groundwater could be considered to be impounded within the surface water catchment.

Apart from evidence such as that presented by Engel (1987), Lewis (1991), and Ferdowsian and Greenham (1992) that geology-related permeability variation in the regolith influenced the development of dryland salinity, there have been no detailed studies of this phenomenon. There have, however, been several general studies of $K_{sat}$ of regolith material in the Western Australian wheatbelt including Peck *et al.* (1980) and George (1992a). These studies suggest that there are potential problems in the measurement of $K_{sat}$ related to the method of drilling.

Peck *et al.* (1980) investigated the $K_{sat}$ of material located generally in the lower 3m of the regolith, immediately above the basement, using a slug test method (Bouwer and Rice, 1976), at five sites in the Darling Range of Western Australia and concluded that the arithmetic mean $K_{sat}$ of this material was 0.036m day$^{-1}$. They concluded that $K_{sat}$ was different in each area that they studied and that at the smallest grid separation (100m) it was essentially random, but at the broad scale bulk $K_{sat}$ was relatively uniform. However, no characterisation of the geology was reported in the study.

George (1992a) described the hydraulic properties of the deep saprolite aquifer for a number of sites in the wheatbelt. The mean $K_{sat}$ of the saprolite aquifer for five catchments based on slug tests of holes drilled by the rotary air blast (RAB) method was 0.57m day$^{-1}$. The aquifer was overlain by an aquitard with a mean $K_{sat}$ of 0.065m day$^{-1}$ (the pallid zone). George (1992a) attributed the difference, greater than an order of magnitude, between his arithmetic mean $K_{sat}$ and that of Peck *et al.* (1980), principally, to the fact that their holes were drilled by the rotary auger method, which smears the clay out on the walls of the holes, thus reducing measured $K_{sat}$. His own results supported this conclusion. He showed that the arithmetic mean $K_{sat}$ for three catchments drilled by the rotary auger method (not the same catchments as those drilled with the RAB technique) was 0.057m day$^{-1}$: an order of magnitude less than for the catchments drilled by the RAB method.

This work suggests that RAB is the preferable method of drilling holes for piezometers, and that statistical analysis of $K_{sat}$ values should treat values obtained from auger holes separately from values obtained from RAB holes.

Because of the complex nature of the interaction between the land vegetation and climate, computer models are needed to investigate where salinity will develop and what the impact of amelioration strategies might be (Dawes and Hatton, 1993). Most of the programs in such studies use topography to control the direction of groundwater flow; because there have been no systematic investigations of geology-related $K_{sat}$ differences in the regolith, they are not taken into account.

One such program was used to model the effect of revegetation on saline outflow into the Wellington Dam and other major water supply reservoirs in Western Australia in order to reduce the salinity of the water, or to prevent its becoming saline (Mauger, 1994). It is a simple, two layer, steady state model which uses a digital elevation model to control the flow of water.

Salama (1994) described techniques to model hydrogeology and develop dryland salinity risk maps Australia-wide. The basis of the process is the automatic classification of the digital elevation data (and therefore the landscape) by a geographical information system (GIS) into 'form facets' (defined by their slope, curvature and aspect) in relation to other catchment attributes (elevation, distance to drainage divide, distance to drainage channel and shape). Whilst this is a more complicated approach than that taken by Mauger (1994), in that the landscape is classified, it is basically the same since they both used a digital elevation model as the principal source of input data and similarly ignored the effect of geological features, except in so far as they impacted on the topography.

In summary then, George (1992a) has shown that there is vertical variation in $K_{sat}$ due to geological differences in the material: the coarse-grained saprolite aquifer has $K_{sat}$ almost an order of magnitude greater than the overlying clay rich pallid zone, and Engel *et al.* (1987) have shown that, in a first order catchment, there is spatial variation in $K_{sat}$ caused by geological differences: the clay produced by the weathering of dolerite is less permeable than the clay and quartz which are the weathering products of granite and granitic gneiss. However, there have been no studies of the effect of regional geological features, such as major faults, on spatial variation in $K_{sat}$ and the impact that this has on groundwater flow and hence on the development of dryland salinity.

This paper investigates the hypothesis that major faults in the wheatbelt of Western Australia explained the location of areas of dryland salinity not explained by topography. Moreover, the causal mechanisms that might underpin a spatial relationship between major faults and dryland salinity were sought.

## Methods

### LOCATION

The locally-named Date Creek catchment is a fourth order stream located some 185km south-southeast of Perth, Western Australia. It is a tributary of the Blackwood River (Fig. 1). Three third order catchments (Study Area 1), one of which is underlain by the Kojonup Fault (Myers, 1989) and forms part of the headwaters of Date Creek have been investigated in detail to establish whether a relationship exists between major faults and the development of salinised land. Two other pairs of similar catchments (Study Areas 2 and 3) within a 20km radius of Study Area 1 have been examined to confirm the observed relationship. One of the catchments in Study Area 2 is underlain by the Kojonup Fault and in Study Area 3 by the Darkan Fault (Myers, 1989) (Fig. 2).

### CLIMATE

Rainfall data were obtained from the Bureau of Meteorology for the five recording stations closest to Study Area 1 and evaporation data were obtained for one of these stations (Table 1). The western wheatbelt of Western Australia is in an area of hot, Mediterranean type climate with hot, dry summers and cool, wet winters. The three study areas lie between the 650 mm and 600 mm isohyets; most rain falls between May and September and for eight months of the year pan evaporation exceeds rainfall.

For the two years during which monitoring of the piezometers has been carried out rainfall was about 75% of the long term average. This implies that the observed

*Table 1.* Climate data from the Bureau of Meteorology.

| Place | Duranillin | Darkan | Collie | Kojonup | Wagin |
|---|---|---|---|---|---|
| Location relative to Study Area 1 | 15km east | 15km northeast | 45km west-northwest | 65km southeast | 65km east-northeast |
| Mean annual rainfall (mm) | 553 | 562 | 957 | 538 | 438 |
| % mean rainfall May–September | 66 | 74 | 77 | 70 | 69 |
| Pan evaporation (mm) | | | | 1443 | |
| Rainfall > pan evaporation | | | | May to August | |

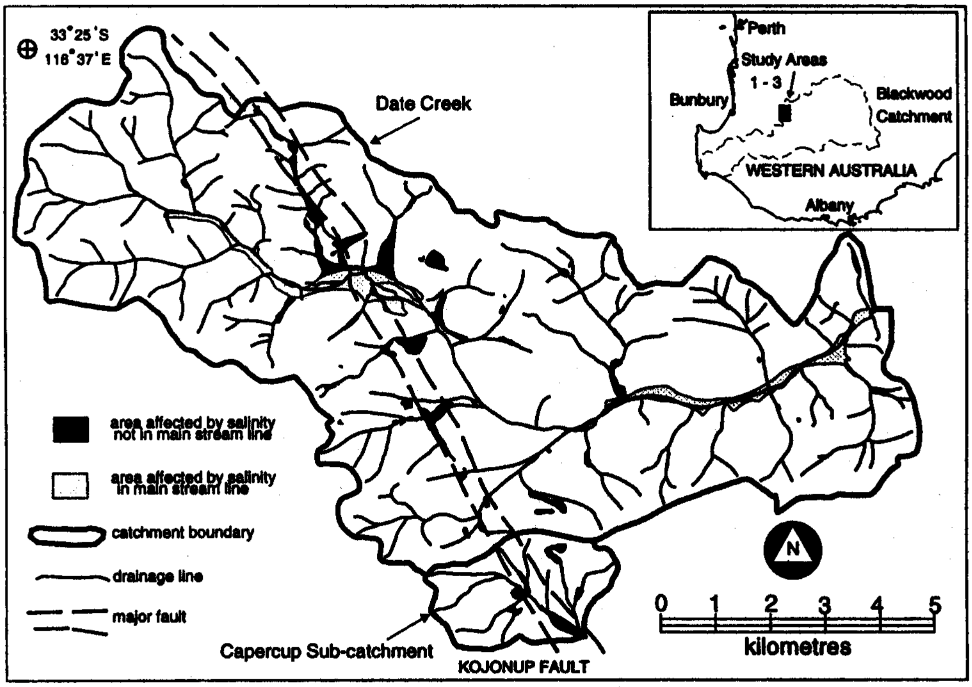


Fig. 1. *Location Plan and Date Creek and the Capercup Sub-catchment showing the distribution of salinised land (both already salt affected in 1991 and predicted to go saline from airphotograph interpretation) in relation to the Kojonup Fault (from WGC, 1994/5).*

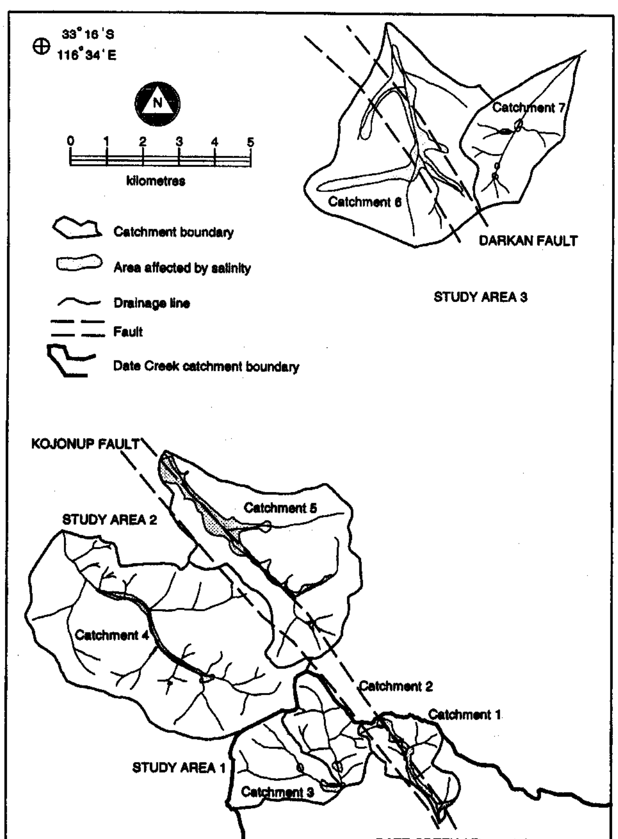


Fig. 2. *Study Areas 1 to 3 showing the distribution of salinised land in relation to the Kojonup and Darkan Faults (from WGC, 1994/5).*

patterns in groundwater levels and rates of water rise are likely to have been occurring at a slower rate than would be the case in a period of average rainfall.

## PHOTOGRAPH AND IMAGE INTERPRETATION

Photointerpretation of Date Creek and the adjoining informally named Capercup Sub-catchment (which is the upper part of the Lake Towerrinning Catchment) has been carried out using the black and white photography flown in 1988/1989 at a scale of 1:50,000 and the colour photography flown in December 1991 at a scale of 1:20,000. Distribution of salinised land was interpreted from the colour photography.

Two classifications of salinised land were used. Severely saline land was represented in the photographs by a bare (except for flooded gums, *Eucalyptus rudis*, and some *Melaleuca* spp.) and often white surface (bare salt). A possible early stage of land salinisation (incipient salinity) was represented in the photography by a darker, mottled tone, presumably because it was still damp when the photographs were taken (early summer), whilst the rest of the landscape had dried out. This photographic tone was accepted as a precursor of bare salt because in two instances in Date Creek, areas with such tone had, by 1994, become areas of bare salt.

Study Area 1 was also investigated by interpretation of the 1991 colour photography. Mapping of salinity was carried out using the same classes as used for Date Creek and these interpretations have been extensively ground truthed. Study Areas 2 and 3 have also been investigated by interpretation of colour aerial photography with limited ground truthing.

### GEOPHYSICS

Two airborne magnetometer surveys of the Study Areas have been interpreted. The first in 1980, was part of a nationwide reconnaissance survey using a fluxgate magnetometer by the then Bureau of Mineral Resources (BMR, now AGSO—the Australian Geological Survey Organisation); flight lines were 1.5km apart, 150m above the ground, and a sampling interval along the flight lines was 60m (BMR, 1981). The second was part of a privately-flown 3,000km$^2$ survey for the Lake Towerrinning Landcare Group (WGC, 1994/5) carried out by Aerodata Limited, a subsidiary of World Geoscience Corporation. The flight lines were spaced at 150m to 300m, and were flown 60m above the ground with a sampling interval of 6m using a caesium magnetometer (Bullock and Isles, 1994).

Several transects using a Geonics EM 31 in vertical mode were completed in two of the catchments of Study Area 1. This instrument measures the apparent electrical conductivity of the land to a nominal depth of 6m (McNeill, 1985).

### PIEZOMETERS

Thirty piezometers were completed in the three catchments of Study Area 1 by Agriculture Western Australia (AgWA) and a private contractor using two similar rotary air blast drilling rigs. The drill cuttings were logged, and assayed for chloride ion concentration by AgWA. These holes were generally drilled as far as the interface between the weathered rock and the crystalline basement rock.

All but one of the holes, which was hammered 15m into the basement, were drilled using a blade bit. The bottom of the holes had a diameter of 100mm. The holes were cased with 50mm PVC pipe with 2m of commercial screen attached at the bottom. This screen was generally located in the coarse grained saprolite aquifer at the interface between the weathered profile and fresh, basement rock (the same layer described by George, 1992a). The screened area was surrounded by a commercial filter pack covered with a bentonite seal and the holes were then back filled with either drill cuttings or cement slurry.

The water levels in these piezometers and the electrical conductivity of the water were monitored monthly from April 1994 to April 1995 and quarterly thereafter, using a 'fox-whistle' plopper attached to a measuring tape and a Eutech Cybernetics TDScan 4 conductivity meter, respectively. Hydrographs of water levels were corrected for density using BORES software, a groundwater database manager developed by AgWA. Where possible the rate of change of water levels with time in the piezometers was calculated from these hydrographs. Longitudinal and cross sections showing ground surface, piezometric pressure surface and depth of the regolith were constructed for Catchment 1 from this data, the drill logs and the topographic contours. All bore holes were surveyed into the Australian Height Datum with a closing error of 5mm.

Slug tests following a method similar to that of Bouwer and Rice (1976) and Bouwer (1989) were carried out on the twenty one of the piezometers which contained water. One bailer of water was removed as rapidly as possible from the piezometer and the recovery of the water levels was measured. Time-drawdown plots were used to calculate the $K_{sat}$ of the material adjacent to the piezometer screen (Bouwer and Rice, 1976).

### GEOGRAPHICAL INFORMATION SYSTEM (GIS) DATABASE

Spatial information and associated tabulated data were stored in AgWA's GIS (which uses Intergraph and Oracle software) and this was used to generate the geomorphometric parameters for the various catchments based on Chorley and Kennedy (1971). The amount of clearing in the seven catchments was determined by subtracting the area of the catchment from the area of remnant vegetation extracted from AgWA's own database. The areas of remnant vegetation in the Study Areas were determined by interpretation of various aerial photograph series from the late 1980s.

## Results and discussion

### THE RELATIONSHIP BETWEEN MAJOR FAULT AND DRYLAND SALINITY

The Kojonup and Darkan Faults are major geological features hundreds of kilometres long (Myers, 1989) and hundreds of metres wide. McIntyre (1980) stated that distinctive magnetic patterns may form in faults for a variety of reasons and Ferdowsian and Greenham (1992) showed that their shear zones were magnetic lows. The Kojonup Fault is represented in WGC (1994/5) as an intense, linear, magnetic low with amplitudes of 150 nT and 210 nT and widths of 500m and 900m at different cut-offs. The width of the fault is variable along its length (Figs 1 and 2) and the magnetic contours show a number of restrictions in its width.

By contrast to its visibility in the geophysical data, the Kojonup Fault is difficult to see in the stereo models of aerial photography, probably because of its size in relation to the size of the individual stereo models. Some photo-lineaments are, however, visible in its vicinity. The fault zones are detectable in Landsat TM data but without the detail observed in the aeromagnetic data; generally small scale images are more easily interpreted then large scale ones.

Minor photolineaments are relatively easy to see in the stereo models. However, dykes are much more difficult, and some of them are impossible, to see. Fortunately, dykes are often represented by magnetic highs (Engel *et al.*, 1987) and the larger dykes (or groups of smaller dykes) are, at least patchily, indicated by magnetic highs in WGC (1994/5).

The magnetic contours of BMR (1981) are less easy to interpret because of the lower data density; however, with the benefit of the detailed WGC (1994/5) data set, it is clear that faults such as the Kojonup and Darkan Faults are represented by a discontinuous series of magnetic lows. It is possible to recognise all the faults contained in Myers (1989) together with some others with an average frequency in the region of one every 8km.

The occurrence of salt in the mainstream lines of catchments is caused by shallow water tables intersecting the valley floors causing saline seepage that is explained by topography. In Date Creek, however, 43% of the salinised land (both bare and incipient salt) is not in the main stream and its occurrence is not explained by its topographic position. Of this salinity, 84% is within a zone 4 km wide centred on the Kojonup Fault; only 16% is in the remaining 12km of the catchment (measured orthogonally to the fault). This demonstrates that there is a strong spatial association between the Kojonup Fault and the present development of dryland salinity in Date Creek. (Fig. 1 and Table 2).

Reconnaissance airphotograph interpretation of about 10, 000km$^2$ centred roughly on Date Creek resulted in the identification of three groups of contiguous third order catchments (one group of three and two groups of two); one of the catchments was underlain by a major fault but the other(s) was not. In these three Study Areas, the faulted catchments have an order of magnitude more salinised land than the unfaulted catchment(s) (Fig. 2 and Table 3). The repetition of this pattern of distribution of salinised land, suggests that this relationship is causal, not just spatial.

## HYDRAULIC CONDUCTIVITY AND THE KOJONUP FAULT

A number of lines of evidence suggest that it is higher values of $K_{sat}$, within and around the fault zone, compared to those outside the zone, that explains the observed differences in salinised land distribution.

Statistical analysis of $K_{sat}$ from Study Area 1 (Table 4) shows that the arithmetic mean from piezometers within the Kojonup Fault is 5.2 times higher than for those outside it ($P$ = 0.09). For the geometric mean, the ratio is 2.9:1 ($P$ = 0.11). Standard t tests were used to determine the significance of whether the two samples were from different populations. Values of $K_{sat}$ within the fault range from 0.198 to 20.79m day$^{-1}$ and outside the fault from 0.014 to 4.65m day$^{-1}$.

The boundaries of large faults such as the Kojonup Fault are not precise linear features but are gradational. The most southerly hole shown in Fig. 3 is on the edge of the fault as interpreted from the magnetic data WGC (1994/5). If this hole is reclassified as being in the fault, the ratio of the arithmetic means inside:outside the fault is

*Table 2.* Salinised areas (both already salt affected in 1991 and predicted to go saline from airphotograph interpretation) that are not in the main streams (NMS) of Date & Capercup Creeks, in relation to the Kojonup Fault. See Figure 1 for the location of the catchments and the Kojonup Fault.

| Catchment | Date | | Capercup | |
|---|---|---|---|---|
| | area(ha) | % NMS | area(ha) | %NMS |
| Total salinised area that is not in the main stream (NMS) | 166 | | 19 | |
| In fault | 76 | 45.8 | 7 | 36.8 |
| < 1km from fault centre line | 48 | 28.9 | 12 | 63.2 |
| >1 <2km from fault centre line | 15 | 9.0 | | |
| >2km from fault centre line | 27 | 16.3 | | |

*Table 3.* Proportion of catchment that is salinised (both already salt affected and predicted to go saline from airphotograph interpretation) in the three Study Areas. See Figure 2 for location of the three Study Areas.

| Study Area | 1 | | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|
| Catchment | 1[a] | 2 | 3 | 4 | 5[a] | 6[a] | 7 |
| Proportion of catchment that is salinised (%) | 11.7 | 0.7 | 0.6 | 2.0 | 11.1 | 14.6 | 1.6 |

[a] Catchment is underlain by a major fault.

*Table 4.* Statistical analysis of $K_{sat}$ data from slug tests of piezometers giving the arithmetic and geometric means, and the significance of the mean differences between samples taken inside, and samples taken outside the Kojonup Fault (all values in m day$^{-1}$). See Fig. 3 for the location of the Kojonup Fault in relation to the piezometers.

| | In Kojonup Fault | Not in Kojonup Fault | In Kojonup Fault | Not in Kojonup Fault |
|---|---|---|---|---|
| | Arithmetic | | Geometric | |
| Number of piezometers | 8 | 13 | 8 | 13 |
| Mean $K_{sat}$ | 5.75 | 1.1 | 1.28 | 0.44 |
| Standard error | 3.1 | 0.39 | 2.49 | 1.35 |
| Significance of mean difference | $P = 0.09$ | | $P = 0.11$ | |
| With one hole reclassified[a] | | | | |
| Number of piezometers | 9 | 12 | 9 | 12 |
| Mean $K_{sat}$ | 5.32 | 1.02 | 1.34 | 0.39 |
| Standard error | 2.78 | 0.41 | 2.08 | 1.42 |
| Significance of mean difference | $P = 0.08$ | | $P = 0.06$ | |

[a] The southern most piezometer in Fig. 3 is very close to the edge of the fault and such margins are gradational.

5.2:1 (P = 0.08) and for the geometric means 3.4:1 (P = 0.06).

Sánchez-Vila *et al.* (1996) concluded that there were scale effects in the measurement of transmissivity (or $K_{sat}$): it increases with increasing scale of the measurement. Their explanation for this scale dependence of transmissivity or $K_{sat}$ is that in natural, heterogeneous systems higher values are better connected than lower values; this leads to effective large-scale transmissivities in heterogeneous systems that exceed the geometric mean of the point values, contrary to what multilog-normal stochastic hydrology predicts, even if the point values for transmissivity are log-normally distributed.

The Kojonup Fault is a large scale heterogeneous system and the work by Sánchez-Vila *et al.* (1996) suggests that the geometric mean of point values will underestimate

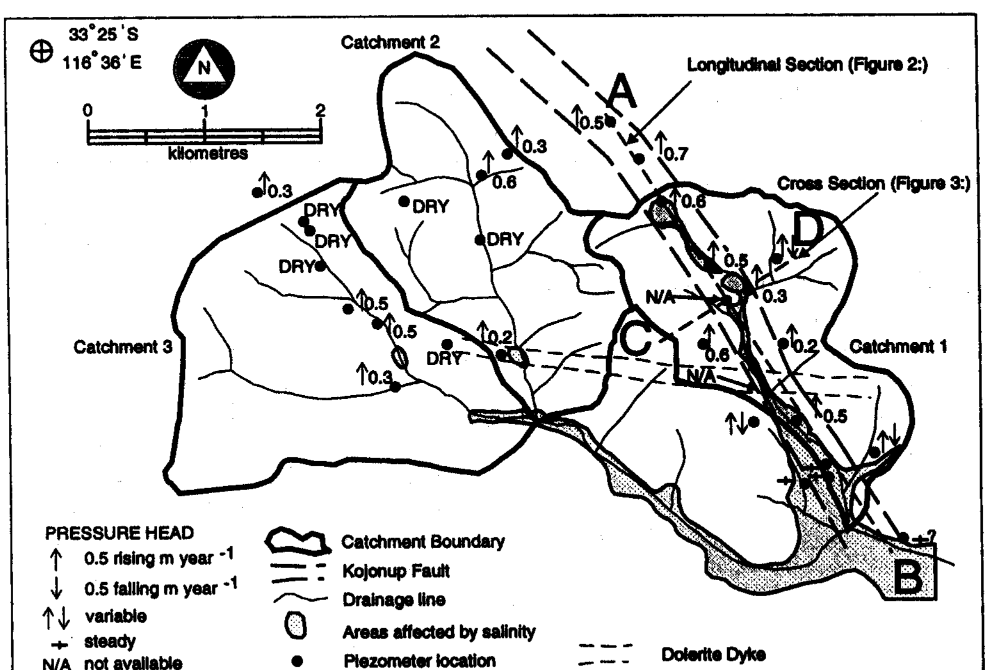


Fig. 3. *Study Area 1 showing changes of piezometric pressure head with time. Twenty five holes were measured monthly for 1 year and quarterly for 9 months, and 5 holes monthly for 2 months and quarterly for 9 months.*

the effective large scale value of $K_{sat}$ for the fault zone. Whilst the arithmetic mean may be an over estimate, Matheron (1967) has shown that it is the upper limit for effective $K_{sat}$ for infinite blocks. The value for $K_{sat}$ for the Kojonup Fault probably lies between the arithmetic and geometric means. The purpose of this study was to obtain a ratio of $K_{sat}$ values for within the fault compared to outside it (rather than absolute values), for use in a hydrological computer model (Clarke *et al.* 1998) and as can be seen above estimates for this ratio are between 5.3:1 and 2.9:1 for the arithmetic and geometric means respectively. The modelling by Clarke *et al.* (1998) shows that with 5 times higher $K_{sat}$ inside the fault there is a similar pattern of salinity in that part of Catchment 1 (the lower part) that is near equilibrium to that shown in Fig. 3; once $K_{sat}$ has been increased further the process is relatively insensitive to change in $K_{sat}$. This supports the conclusion that, to a first approximation, $K_{sat}$ within the fault zone is about five times higher than that outside it.

The $P$ values for the significance of the difference between the means are higher than those accepted normally ($P < 0.05$) but $P = 0.06$–$0.11$ still means that there is an 89–94% probability that the two populations are different. Other pieces of evidence, taken with the statistical analysis and the modelling carried out by Clarke *et al.* (1998), suggest that these $P$ values do represent geologically significant differences between the populations inside and outside the fault.

Firstly, the frequency distribution (Fig. 4a) shows that $K_{sat}$ values are not less than bimodally distributed and possibly are polymodal and the log probability plot of cumulative frequency of $K_{sat}$ (a technique that is designed to separate a sample into its log-normal populations as straight lines with different slopes, Fig. 4b) shows that sample values do, in fact, come from two separate populations. However, these populations are not simply inside and outside the fault. Population 1 corresponds generally to faulted material, whilst Population 2 generally represents material which has not been affected by faults. However, both populations include values from within the Kojonup Fault and outside it. The arithmetic mean of $K_{sat}$ for Population 1 is more than twenty five times higher than that for Population 2 ($P<0.05$) (Table 5).

*Table 5.* Statistical analysis of $K_{sat}$ data from slug tests of piezometers from Populations 1 and 2 from Fig. 4b (all values in m day$^{-1}$).

| | Population 1 | Population 2 |
|---|---|---|
| Number of piezometers | 8 | 13 |
| Arithmetic mean $K_{sat}$ | 7.07 | 0.27 |
| Standard error | 2.81 | 0.04 |
| Significance of mean difference | $P<0.05$ | |

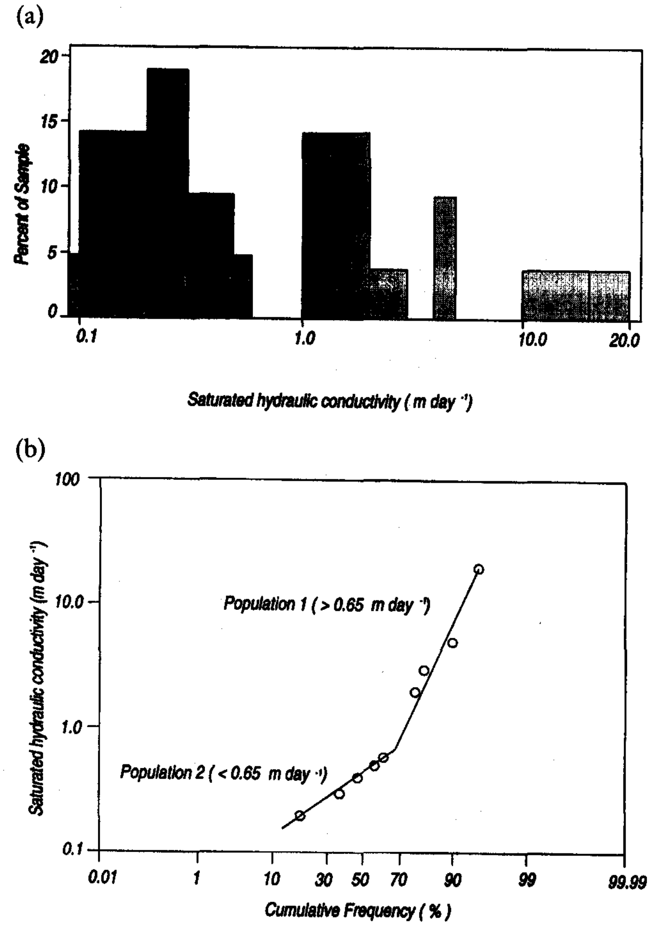


Fig. 4 (a) *Frequency distribution of $K_{sat}$ data from slug tests of piezometers in Study Area 1 (see Figure 3).* (b) *Cumulative frequency log—probability plot of Ksat data from slug tests of piezometers in Study Area 1 (see Figure 3).*

The lower statistical significance and the presence of both high and low values of $K_{sat}$ both within and outside the fault are to be expected. Testing the $K_{sat}$ of a small volume of material around piezometers is not likely to produce a value characteristic of a large, heterogeneous system. Major faults are large heterogeneous systems and are likely to contain zones within them of both high and low $K_{sat}$ (the latter perhaps caused by dolerite dyke material within the fault) although their overall $K_{sat}$ is higher than the surroundings. Even if these surroundings generally have lower $K_{sat}$, they may contain zones of higher $K_{sat}$ in minor faults. Indeed in the present study, minor faults, represented in aeromagnetic data by narrower and less intense curvilinear lows than major faults, were evident outside the Kojonup Fault zone suggesting that they may be the source of some of the variance in $K_{sat}$ outside the zone. Thus, measurement of $K_{sat}$ is likely to produce both high and low values, both within and outside major faults (which agrees with the observations), therefore lower statistical significance than normal standards is to be expected: however, it does not mean that the differences

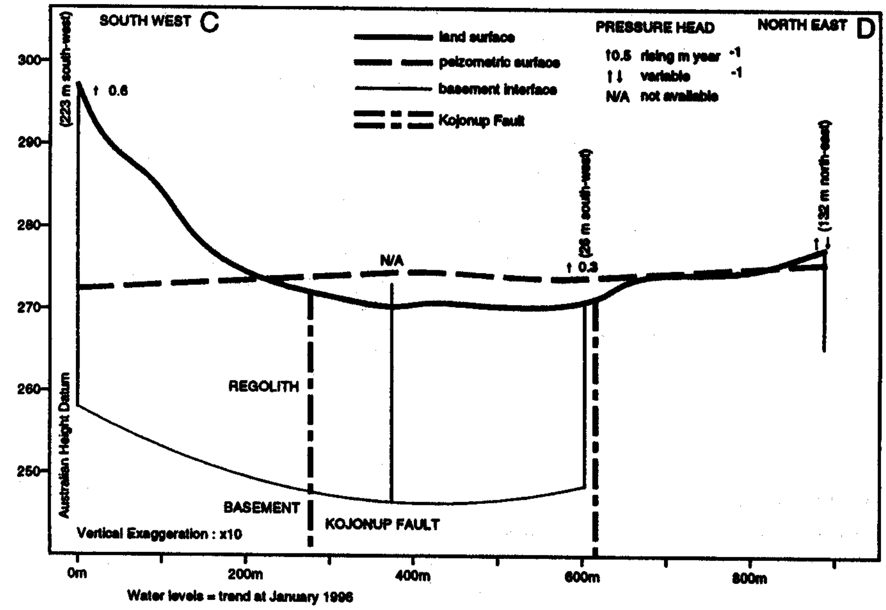


Fig. 5. *Cross section C–D across Catchment 1. See Fig. 3 for location of section.*

are not actually significant geologically. This is supported by the presence of both high and low values, and values from within and outside the fault, in both Populations 1 and 2 (Fig. 4b), although Population 1 is mainly faulted material and Population 2 is mainly material that is not affected by faults, and the mean of Population 1 is much higher than that for Population 2.

Secondly, other independent evidence supports the view that the $K_{sat}$ in the Kojonup Fault is indeed higher than it is outside it, if not by how much.

It was noted that the shape of the piezometric surface in Catchment 1 was atypical compared to that reported for most other catchments in southwestern Australia. Other studies of catchment hydrology in southwestern Australia have established that the piezometric surface in a valley mimics the topography, but with reduced amplitude: the surface water and groundwater catchments are coincident. Low $K_{sat}$ in the regolith of unfaulted valleys limits the flow of groundwater down the pressure gradient resulting in this characteristic shape of the piezometric surface. Typical local examples of this phenomenon include Salama *et al.* (1993a) at the Cuballing Catchment north of Narrogin and Peck and Williamson (1987) at the Wights Catchment in the Collie River Basin (Table 6).

By contrast, the cross section (Fig. 5) shows that the piezometric surface across Catchment 1 is almost flat with a very gentle dip to the west despite the existence of a 15m topographic difference tacross the valley. Since the $K_{sat}$ is not sufficiently low to hold up a difference in pressure head as is the case in other catchments (Salama *et al.*, 1993a and Peck and Williamson 1987), this suggests higher $K_{sat}$ in the fault zone.

Water levels in the longitudinal section (Fig. 6) also exhibit anomalous patterns which suggest that $K_{sat}$ in the fault zone is higher than outside it. The water level falls continuously from Three Mile Gully, under the topographic (and therefore surface water) divide, to the lower end of Catchment 1, some 4.5km away. Thus, by contrast

*Table 6.* A comparison in elevation differences of piezometric surfaces and topography for three catchments.

| | Elevation Difference[a] (m) | |
|---|---|---|
| Catchment | Piezometric Surface | Topographic Surface |
| Catchment 1 Study Area 1[b] | +1 | −15 |
| Cuballing[c] | −10 | −12 |
| Wights[d] | −18 | −24 |

[a] Positive elevation difference indicates a convex surface, negative a concave one.
[b] See Fig. 5.
[c] Salama *et al.* (1993a).
[d] Peck and Williamson (1987).

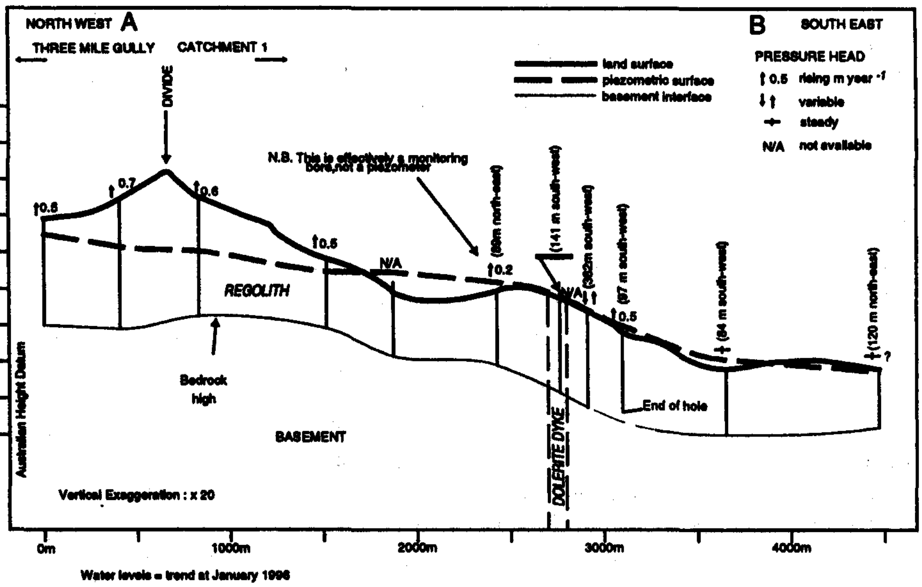


Fig. 6. *Longitudinal section A–B along Catchment 1. See Fig. 3 for location of section.*

with the catchments described by Salama *et al.* (1993a) and Peck and Williamson (1987), in the faulted catchment of Study Area 1 the surface water and groundwater divides are not coincident. The piezometric surface in the piezometer drilled within the dolerite dyke is 10m higher than the local piezometric surface within the fault and most probably represents an influx of groundwater, channelled by the dyke, into the fault, from upslope to the east. More piezometers, along the strike of the dyke would be needed to test this hypothesis. If there is hydraulic connection between the piezometers, as indicated by the piezometric heads, it suggests that $K_{sat}$ within the Kojonup Fault is higher than outside, since it is not sufficiently low to hold up a difference in pressure heads under the divide as it does elsewhere (Peck and Williamson, 1987 and Salama *et al.*, 1993a). George (1992b) demonstrated that groundwaters within the Belka Catchment had a flat piezometric surface under the surface water divide and showed that this was along strike from a major fault. He could find no surface evidence of a fault within the catchment, but he did not have a detailed aeromagnetic survey available such as WGC (1994/5) which was used in the present research. By analogy with Study Area 1, it would seem likely that there is indeed a fault running through the Belka Catchment.

Elsewhere in the wheatbelt of Western Australia, bedrock highs can cause dryland salinity by reducing the piezometric gradient (Salama *et al.*, 1993b) but, within Catchment 1, the bedrock high to the southwest of the divide does not have this effect. This also suggests that $K_{sat}$ within the fault is high because thinning of the regolith does not decrease trasmissivity substantially.

Sporadic observation of streamflow in Study Area 1 showed that the central part of the creek in Catchment 1 flowed continuously whilst those in Catchments 2 and 3 flowed only in response to winter rainfall. This could be explained by the higher $K_{sat}$ in Catchment 1 resulting in the piezometric surface being lower under the slopes and higher under the valley floor than would be expected in an unfaulted situation which causes the piezometric surface to intersect the land surface for part of the catchment (Fig. 5). The zone of seepage in Catchment 1 is that part of the catchment where the piezometric surface is above ground level.

The last three pieces of evidence (the longitudinal and cross sections, and the comparison of streamflow) are qualitative, if not quantitative, measures of $K_{sat}$, but all point to higher $K_{sat}$ within the fault zone than outside it . The movement of water in the fault system appears to be smoothing out, or 'averaging', the heterogeneity which causes problems with smaller scale measurement indicating that $K_{sat}$ within the fault is higher, if not by how much.

Comparison of the results in Table 4 with those of George (1992a) shows that only one of his catchments exceeds the arithmetic mean of $K_{sat}$ values outside the Kojonup Fault and the arithmetic mean of George's catchments is only 56% of the arithmetic mean for those piezometers outside the fault in this study. It is, therefore, possible that all the measurements of $K_{sat}$ in Study Area 1 are affected by the influence of the Kojonup Fault; those within it (from WGC, 1994/5) are more affected than those outside it. The arithmetic mean of $K_{sat}$ within the fault itself is an order of magnitude higher than that from George (1992a). The distribution of salinised land in Date Creek and the Capercup Sub-catchment (Fig. 1 and Table 3) supports this conclusion: 84% of the salinised land that was not in the main stream was located within 2km of the centre line of the fault. Most of the piezometers in Study

Area 1 are less than 2km from the centre line of the Kojonup Fault. However, it is possible that the area studied has higher $K_{sat}$ than other parts of the wheatbelt.

### OTHER POSSIBLE MECHANISMS UNDERLYING THE RELATIONSHIP BETWEEN MAJOR FAULTS AND DRYLAND SALINITY

Other potential causes of the observed relationship between major faults and dryland salinity were investigated to see if a difference in $K_{sat}$ was the only factor affecting the relationship.

#### *Geomorphology*

The reasonable similarity of geomorphometric parameters between faulted and unfaulted catchments within each Study Area demonstrates that their major differences in salinised land distribution are not caused by differences in the geomorphology (Table 7). The quite distinct geomorphometric differences between Study Areas (there are greater differences between Study Areas than there are within them) demonstrate that this relationship between major faults and the development of dryland salinity persists across a variety of landscapes. It also supports the conclusion that the geomorphometric parameters are indeed similar within Study Areas despite the differences that do exist.

#### *Depth of regolith and salt store*

The depths of the regolith in the three catchments of Study Area 1 are similar so this does not explain the differences in the development of salinised land (Table 8). The lack of significant differences between the mean chloride ion concentrations for the full regolith depth of the three catchments of Study Area 1 (Table 9), combined with the similarity in regolith thickness, demonstrates that the salt store is the same in all three catchments. Thus the observed differences in salinised land distribution cannot be explained by differences in salt store.

*Table 8.* Depth of regolith in Study Area 1.

| Catchment | 1 | 2 | 3 |
|---|---|---|---|
| Depth of regolith (m) | 23.5 | 20.3 | 21.0 |
| Standard error | 2.0 | 5.6 | 4.7 |
| Number of piezometers | 12 | 5 | 5 |

The electromagnetic results show no difference between the faulted catchment and the adjacent unfaulted catchment in Study Area 1 (Table 10). The correlation between EM31 vertical readings and chloride ion concentration to 6m depth is highly significant (Table 11); therefore these data support the conclusion that there is no difference in salt store between the three catchments of Study Area 1.

#### *Cleared area*

Although there are differences in cleared areas of the catchments within the Study Areas, they do not correlate with the observed differences in salinised land distribution (Table 14). In Study Areas 1 and 2, the faulted catchment is more cleared than those not faulted; in Study Area 3, it is the other way round. In addition, the maximum difference in degree of clearing is two and a half times (Study Area 2), but the difference in salinised land development is an order of magnitude.

Peck and Williamson (1987) showed that water levels rose strongly after half of the Lemons catchment was cleared in 1977 and unpublished research (Clarke and Bell) into a catchment 20km north of Narrogin showed that salinity was developing in a catchment that was only 27% cleared. These last observations demonstrate that salinised

*Table 7.* Geomorphometric characteristics for the three Study Areas.

| Study Area | 1 | | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|
| Catchment | 1[a] | 2 | 3 | 4 | 5[a] | 6[a] | 7 |
| Size dependant variables | | | | | | | |
| Total drainage length (m) | 10,363 | 10,629 | 10,238 | 35,838 | 17,833 | 17,281 | 11,138 |
| Main stream length (m) | 3,665 | 3,388 | 3,587 | 8,593 | 7,275 | 6,151 | 4,808 |
| Area (ha) | 426 | 448 | 556 | 2,861 | 1,763 | 1,875 | 758 |
| Elevation difference (m) | 57 | 57 | 60 | 60 | 60 | 65 | 50 |
| Perimeter (m) | 11,500 | 9,448 | 10,693 | 23,760 | 20,310 | 18,800 | 12,200 |
| Size independent variables | | | | | | | |
| Circularity[b] | 0.405 | 0.631 | 0.622 | 0.637 | 0.537 | 0.667 | 0.640 |
| Drainage density[c] (m $ha^{-1}$) | 24.9 | 23.7 | 18.4 | 12.5 | 10.1 | 9.2 | 14.7 |
| Relative relief[d] | 0.496 | 0.603 | 0.561 | 0.253 | 0.295 | 0.346 | 0.410 |

[a] Catchment is underlain by a major fault. See Fig. 2.
[b] Circularity = area divided by area of a circle with the same perimeter
[c] Drainage density = total drainage length divided by area
[d] Relative relief = 100 times the elevation difference divided by the perimeter

*Table 9.* Drillhole chloride ion concentrations for the entire regolith in Study Area 1.

| Catchment | Number of drillholes | Arithmetic mean chloride ion % | Standard error |
|---|---|---|---|
| 1[a] | 14 | 0.09 | 0.04 |
| 2 | 5 | 0.09 | 0.04 |
| 3 | 7 | 0.05 | 0.04 |
| 2 and 3 | 12 | 0.07 | 0.05 |

[a] Catchment is underlain by a major fault. See Fig. 3.

*Table 10.* Results of ground electromagnetic traverses in Study Area 1 (using a Geonics EM31 in vertical mode).

| | $dSm^{-1}$ | Standard Error | Length of Transect Section (m) | Standard Error | Number of Transects |
|---|---|---|---|---|---|
| Catchment 1[a] | 1.1 | 0.2 | 308 | 164 | 6 |
| Catchment 2 | 1.1 | 0.2 | 205 | 94 | 5 |

[a] Catchment is underlain by a major fault. See Fig. 3.

*Table 11.* Drillhole chloride ion concentrations in the top 6m.

| Status by reference to WGC (1994/5) | Number of drillholes | Arithmetic mean chloride ion % | Standard error |
|---|---|---|---|
| In fault | 10 | 0.063 | 0.080 |
| Not in fault | 19 | 0.046 | 0.052 |

*Table 12.* Cleared areas of catchments.

| Study Area | 1 | | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|
| Catchment | 1[a] | 2 | 3 | 4 | 5[a] | 6[a] | 7 |
| Proportion of catchment that is cleared (%) | 83.7 | 69.4 | 66.2 | 36.5 | 90.4 | 75.5 | 87.9 |

[a] Catchment is underlain by a major fault. See Figure 2.

land will develop in catchments where the proportion cleared is quite low and indeed, in the last case, where it is less than that in any of the Study Areas.

### *Groundwater flow through catchment divides*

This research has shown that there is a strong spatial relationship between major faults and the development of dryland salinity and that the most plausible causal mechanism underlying the relationship is higher $K_{sat}$ inside the fault zone compared to outside it. It has also demonstrated that differences in geomorphology, salt store, regolith thickness, and degree of clearing are not responsible for the relationship.

In Study Area 1, the sequential drop of the piezometric levels in the longitudinal section along the fault zone (Fig. 6) from Three Mile Gully into Catchment 1 (assuming hydraulic connection as inferred by the piezometers) suggests that groundwater can flow from one surface water catchment into another as suggested by Lewis (1991); she concluded that she could not answer the questions how much, how far and how fast? From a study in the East Belka Catchment in an area with 300mm mean annual rainfall George (1992b) concluded that, although the flat piezometric surface below a surface water divide (along strike from a fault) could allow groundwater to flow albeit slowly between surface water catchments, the groundwater was effectively impounded within the catchment.

With the evidence now available from the present study, it is possible to investigate to a first approximation whether significant volumes of ground water can flow beneath topographic divides, and to attempt to answer the questions posed by Lewis (1991). The longitudinal section (Fig. 6) indicates that transport is possible over at least 4.5km. The distance is potentially greater than this since the ground level rises again a short distance to the northwest of the most northwesterly hole in Three Mile Gully.

Although flow in major faults is probably not Darcyan, Darcy's Law can be used to obtain approximate answers to the questions how much and how fast. These calculations suggest that the lateral flow is approximately 30,000m$^3$ year$^{-1}$ in the area of the four holes under the divide between Three Mile Gully and Catchment 1, based on $K_{sat}$ 5.3m day$^{-1}$ (Table 4), width 600m (from WGC, 1994/5), head difference 10m (Fig. 6), length 1,800m (Fig. 6), thickness of the saprolite aquifer 4m from the drill logs (unpublished data), and saturated thickness of the aquitard 16m (Fig. 6).

The area of Catchment 1 is 426ha; therefore this volume of water flowing through the surface water divide is equivalent to an annual recharge of approximately 7mm over the entire catchment. If the recharge from within the surface water catchment is about 60mm (10% of rainfall, after Loh and Stokes, 1981), this additional recharge represents a further 11% and could explain the significantly greater amount of salinised land in Catchment 1 than in Catchments 2 and 3.

As was noted by George *et al.* (1991), it will be necessary in future, at least in areas where there are major faults, to extend the present focus on catchment management (Nulsen, 1986) to landscape management. Even if the farmers in Catchment 1 implement treatments to reduce the amount of salinised land in the catchment to near zero, there may still be more than 7mm of recharge coming through the divide. To be effective, the treatment will have to lower the piezometric surface in Catchment 1 by about 5m, to get it 2m below the ground surface. However, such an increase in head difference across the divide could increase the volume flowing through the divide to approximately 40,000m$^3$ year$^{-1}$ or about 10mm of annual recharge over the entire catchment.

The piezometric surface in the most northwesterly hole shown in the longitudinal section (Fig. 6) is rising at 0.5m year$^{-1}$; potentially, this could continue until it reaches the ground surface: a rise of about 9m. If the piezometric surface does rise by this amount and the farmers do cause a 5m drop in the piezometric surface in Catchment 1, the piezometric height difference across the divide would become 24m and the volume of water flowing through the divide about 70,000m$^3$ year$^{-1}$; or the equivalent of 16mm of recharge, an additional 27%. This means that, potentially, the treatments might have to handle an additional 16 to 27% of recharge and would therefore have to be considerably more intense.

## General discussion and conclusions

Whilst the relationship between the development of salinised land and topography is important, the present results show that a significant amount of such salinisation in the western wheatbelt of Western Australia cannot be explained by topography alone. The faulted catchments in each of the Study Areas have geomorphology similar to the unfaulted catchments but the area of salinised land in the former is much greater. This demonstrates clearly the importance of major faults in the development of salinised land and implies that other geological features may also be important. Thus, understanding of the geological variation is necessary in order to predict accurately the location and extent of dryland salinity. Computer programs based only on elevation models would not predict the observed differences in salinity distribution in the three Study Areas and management strategies that do not take geological variation into account may not deliver the expected result. For example, there were extensive plantings of trees about nine years ago in the lower parts of Catchment 5 (which is underlain by the Kojonup Fault) and these appear to be healthy and growing well (and therefore should be beginning to have an impact); however field observation shows that salinity is still spreading slowly. This may be because the fault is having an impact on groundwater flows that was not taken into account in the computer model used to design the revegetation pattern.

Interpretation of the western third of the 1:250,000 Collie aeromagnetic map (BMR, 1981) shows that faults similar to the Kojonup and Darkan Faults occur on average every 8km. Analysis of the salinised land distribution in Date Creek and the Capercup Sub-catchment shows that the Kojonup Fault has a zone of influence on it that is up to 4km wide. Thus, 50% of the landscape in this region could be subject to the influence of these faults on the development of dryland salinity. Brief inspection of parts of the BMR aeromagnetic survey in other areas shows that, whilst faults may not be as frequent in some parts of the wheatbelt of Western Australia, they are present in many places.

The Kojonup and Darkan Faults are major geological features, hundreds of kilometres long and hundreds of metres wide. The fact that 43% of the salinised land (both bare and incipient salt) in Date Creek is not in the main stream, and that 84% of this salinity is within 2km of the centre line of the Kojonup Fault demonstrates a strong spatial association between the Kojonup Fault and the present development of dryland salinity in Date Creek. The repetition of the distribution of salinised land in the three Study Areas, suggests that this relationship is causal, not just spatial.

It is concluded that $K_{sat}$ within major fault zones is higher than in their immediate vicinity (and to a first approximation five times higher) and that this is the mechanism underlying the relationship between the faults and dryland salinity. Based on hydraulic head differences, it was concluded that water can be transmitted through these major faults, underneath surface water divides, for distances up to several kilometres and at a rate which is significant compared to rates of recharge from rainfall over the receiving catchment. Since recharge management in the receiving catchment would increase the head difference, this recharge could then increase further, depending on how far the piezometric surface in Three Mile Gully continues to rise. It is clear from the present results, showing the potential for transmission of significant volumes of water through major faults, under surface water divides, that future efforts to ameliorate salinised land will need to concentrate on landscape, not just catchment, scaled treatments. Other geological features in the region, such as the widespread Tertiary sediments, will also have the potential to transmit water beneath surface water divides (George *et al.*, 1994). The existence of these two geological features capable of transmitting water beneath surface water divides (and there may be others), suggests that consideration of surface water catchments as the primary landscape unit for managing dryland salinity may often fail to predict all the areas of land that are likely to become salinised and may lead to rehabilitation techniques that fail to reverse the problem.

The magnitude of the effect that geological features, such as major faults, have on the hydrogeology of a region is such that revegetation treatment strategies, and the (computer) models used to generate them, will have to take such features into account. For this to happen, data locating these geological features over wide areas must be readily available to the modellers; the location of major faults by interpretation of airborne magnetic data can satisfy this criterion. More research is needed to establish what other geological features in the region are significant hydrogeologically and what means may be used to map them rapidly and cheaply over wide areas.

## Acknowledgments and declaration

Except where stated in the text, this research and interpretation was carried out by the principal author towards the degree of Doctor of Philosophy from Murdoch University, Western Australia, whilst receiving an Australian Postgraduate Award, and supervised by the other authors. The research was funded, in part, by an Australian Research Council collaborative grant together with the Water and Rivers Commission (WRC) and AgWA.

The authors would like to thank Geoff Mauger (WRC) and Greg Beeston (AgWA) for their help and contribution to the research effort, the Lake Towerrinning Catchment Group for paying for part of the detailed aeromagnetic survey with funds provided by Landcorp and the local farmers for their cooperation. Sincere thanks are also due to Mic Andacich (AgWA) for creating the Figures.

## References

Barrett-Lennard, E.G. and Nulsen, R.A., 1989. Dryland soil salinity—cure, containment or catastrophe *Proc. 5th Aust. Agron. Conf.* Perth, 304–311.

BMR, 1981. *Collie 1:250,000 Sheet Total Magnetic Intensity*, BMR, Canberra.

Bouwer, H., 1989 The Bouwer and Rice slug-test—an update. *Groundwater* 27(3):304–409.

Bouwer, H., and Rice, R.C., 1976. A slug-test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Wat. Resour. Res.* 12:423–428.

Bullock, S.J., and Isles, D.J., 1994. Airborne geophysics in Western Australia, in Geophysical signatures of Western Australian Mineral Deposits, Geology and Geophysics Department (Key Centre) and UWA Extension, Univ., West., Aust., Publication No.26, 85–103.

Chorley, R.J., and Kennedy, B.A., 1971. *Physical Geography—A Systems Approach* Prentice-Hall International Inc, London.

Clarke, C.J., Mauger, G.W., Bell, R.W., and Hobbs, R.J., 1998. The design and effect of revegetation strategies for the western wheatbelt of Western Australia. Part 2: the interaction between revegetation strategies and major fault zones. *Aust. J. Soil Res.* **36**: 131–142.

Dawes, W., and Hatton, T., 1993. *TOPOG_IRM 1. Model description*. CSIRO Division of Water Resources, Technical Memorandum, 93/5.

Engel, R., McFarlane, D.J., and Street, G., 1987. The influence of dolerite dykes on saline seeps in southwestern Australia. *Aust. J. Soil Res.*, **25**: 125–136.

Ferdowsian, R., and Greenham, K.J., 1992. *Integrated Catchment Management Upper Denmark Catchment*. Dept. Agric. West. Aust., Technical Report 130, Perth.

Ferdowsian, R., George, R.J., Lewis, M.F., McFarlane, D.J., Short, R., and Speed, R., 1996. The extent of dryland salinity in Western Australia, *Proceedings, Productive Use of Saline Lands Conference*, Albany, Western Australia, 89–97.

George, R.J., 1992a. Hydraulic properties of groundwater systems in the saprolite and sediments of the wheatbelt, Western Australia. *J. Hydrol.*, **130**: 251–278.

George, R.J., 1992b. Groundwater processes, sandplain seeps and interactions with regional aquifer systems in South-Western Australia *J. Hydrol.*, **134**: 247–271.

George, R.J., McFarlane, D.J. and Lewis, M.F., 1991. A review of recharge and implications for management of saline agricultural catchments, Western Australia. *Institution of Engineers Australia*, Conference 91/22, 193–197.

George, R.J., Cochrane, D.L., and Bennett, D.L., 1994. Groundwater systems responsible for dryland salinity in the Lake Towerrinning catchment, Western Australia., Proc. *Water Down Under 94*, Congress of the International Association of Hydrogeologists and International Hydrology and Water Resources Symposium, Adelaide, 2: 355–360

GSWA, 1990. *Geology and Mineral Resources of Western Australia.*, P.E. Playford (Ed.), Geol. Surv. West. Aust., Memoir 3, Perth.

Hingston, F.J. and Gailitis, V., 1976. The geographic variation of salt precipitated over Western Australia. *Aust. J. Soil Res.*, **14**: 319–335.

Johnson, C.D., 1987. Distribution of environmental chloride in relation to subsurface hydrology. In: A.J. Peck, and D.R. Williamson (Eds) Hydrology and salinity in the Collie River Basin, Western Australia. *J. Hydrol.*, **94**: 67–88.

Lewis, M.F., 1991. Lineaments and salinity in Western Australia—carriers or barriers? *Proc. International Hydrology and Water Resources Symposium*, Perth: 202–209.

Loh, I.C. and Stokes R.A., 1981. Predicting stream salinity changes in southwestern Australia. *Agric. Wat. Manage.*, **4**: 227–254.

Matheron, G., 1967. *Elements pour une theorie des milieux poreux*. Maisson et Cie, Paris.

Mauger, G.W., 1992. pers. comm. Supervising Engineer, Water Authority of Western Australia.

Mauger, G.W., 1994. Hydrologic assessment of vegetation in catchments affected by dryland salinity in southwestern Australia, Proc. *Water Down Under 94*, Congress of the International Association of Hydrogeologists and International Hydrology and Water Resources Symposium, Adelaide, 2: 379–500.

McArthur, W.M., 1991. *Reference Soils of South-western Australia*. Department of Agriculture Western Australia and the Australian Soil Science Society, Perth.

McArthur, W.M., 1993. History of landscape development. In R.J. Hobbs and D.A. Saunders (Eds), *Reintegrating Fragmented Landscapes Towards Sustainable Production and Nature Conservation*, Springer-Verlag, New York: 10–22.

McArthur, W.M., Churchward, H.M., and Hick, P.T., 1977. *Landforms and Soils of the Murray River Catchment Area of Western Australia*. Land Resources and Management Series No. 3, CSIRO, Australia.

McArthur, W.M., Turner, J., Lyons, W.B. and Thirwill, M.F., 1989. Salt sources and water-rock interaction on the Yilgarn Block, Australia: Isotopic and major element tracers. *Appl. Geochem.* 4:79–92.

McIntyre, J.I., 1980. Geological significance of magnetic patterns related to magnetite in sediments and metasediments., *Bull. Aust. Soc. Explor. Geophys.*, 11:19–33.

McNeill, J.D., 1985. Rapid, accurate mapping of soil salinity using electromagnetic ground conductivity meters. Technical Note TN-18, Geonics Ltd., Mississauga, Ontario, Canada.

Mulcahy, M.J., Churchward, H.M., and Dimmock, G.M., 1972. Landforms and soils on an uplifted peneplain in the Darling Range, Western Australia. *Aust. J. Soil Res.* **10**: 1–14.

Myers, J.S., 1989. *Australia 1:1,000,000 Geological Series, Albany Map*, Geol. Surv. West. Aust., Perth

Nulsen, R,A.,1986. Management of salt affected land. *Reclam. Reveg. Res.* 5:197–209.

Peck, A.J., and Williamson, D.R. 1987 Effects of forest clearing on groundwater. In: A.J. Peck and D.R. Williamson. (Eds) Hydrology and salinity in the Collie River Basin, Western Australia. *J. Hydrol.*, **94**: 47–66.

Peck, A.J., Yendle, P.A., and Batini, F.E., 1980. Hydraulic conductivity of deeply weathered materials in the Darling Range, Western Australia. *Aust. J. Soil Res.* 18: 129–138.

Salama, R.B., 1994. The use of GIS in groundwater studies and modelling and dryland salinity risk maps. *Proc. Resource Technology '94*, Melbourne: 489–500.

Salama, R.B., Farrington, P., Bartle, G.A., and Watson, G.D., 1993a. Salinity trends in the wheatbelt of Western Australia: results of water and salt balance studies from Cuballing catchment. *J Hydrol.* 145: 41–63

Salama, R.B., Farrington, P., Bartle, G.A., and Watson, G.D., 1993b. The role of geological structures and relict channels in the development of dryland salinity in the wheatbelt of Western Australia, *Aust. J. Earth Sci.* **40**: 45–56.

Sánchez-Vila, X., Carrera, J., and Girardi, J.P., 1996. Scale effects in transmissivity. *J. Hydrol.* **183**: 1–22.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In V.T., Chow (Ed) *Handbook of Applied Hydrology* McGraw-Hill, New York.

WGC, 1994/5. The Lake Towerrinning Area Airborne Magnetometric and Radiometric Survey, World Geoscience Corporation, Perth, unpubl.

Wood, W.E., 1924. Increase of salt in soil and streams following the destruction of the native vegetation. *J. Roy. Soc. West. Aust.*, **10**: 35–47.